CENTRIFUGE MODELING OF EARTHQUAKES

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Abstract. The major problem in scale modeling of crustal tectonic processes, namely, the requirement for a brittle modeling material of extremely low strength (∿0.1 bar) can be overcome by doing model tests under artificial gravity in a centrifuge. When conditions of dynamic similarity are observed, scale modeling, because of its controlled nature, can be an important tool supplementing field investigation, theoretical study, and numerical simulation of crustal tectonic processes. Fracture events by simulated tectonic stress loading in a model thrust fault (model dimensions: 20 cm depth x 25 cm x 27 cm) have been generated when the model is subject to 50 g in a centrifuge of 1.53 m radius. Measurements obtained are: the total loading force, the stress change at one location inside the fault zone, and model seismic signals recorded on the model top surface. With use of a scaled brittle model material, the model scales up to a prototype approximately 2.2 km depth x 2.8 km x 3.0 km in dimensions.

Introduction

Shallow tectonic earthquakes occur on existing faults or weak zones within the earth's crust. The volume of rock involved in an earthquake and the strain distribution surrounding the fault depend on the material properties surrounding and inside the fault zone and on the tectonically-developed stress pattern which generates the earthquakes. The stress pattern depends very much on the local geological structure. The material property in the locked parts of the fault can be characterized by static friction between two rock masses with or without a layer of gouge material sandwiched in between. The material property in the unlocked parts of a fault can be characterized by creep in a fault zone of finite width. Since these properties depend on the total stress acting on the material (Friction depends on the normal stress acting on the fault surfaces and creep depends on the total stress acting on the gouge material.) which in turn depends on the gravitational body forces, gravitational effects are important for deformation surrounding geologic faults.

Field investigations are essential in monitoring any particular structure for its potential geological hazards. The process, however, is slow because of the long time scale involved in tectonic processes. Numerical modeling serves a useful function in understanding and predicting possible events on a geological structure. However, numerical modeling involving finite deformation requires assumptions of material constitutive relations which may or may not be realistic so that it needs verification by laboratory experiments. Scale modeling can therefore be an important tool supplementing both field investigation and numerical modeling of crustal tectonic processes. We shall demonstrate in this research letter that dynamic similarity in scale modeling of shallow earthquakes can be achieved by doing a faulting experiment in a centrifuge.

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Principles of Centrifuge Modeling of Earthquakes

The principles of physical similarity and methods of model testing are well known and have been extensively used in engineering disciplines (e.g. Sedov, 1959) to model structures of complicated shape or material properties, or which otherwise present difficulties in analysis. We shall illustrate the applicability of model testing in a centrifuge to produce physically similar results in crustal tectonic problems by the following: Consider three-dimensional deformation and fracture associated with a fault in a crustal block. The local stress equation is

$$\sum_j \frac{\partial \sigma_{ij}}{\partial x_j} + \rho Z_i = \rho a_i, \quad i=1,3 \qquad (1)$$

σ_{ij} : total stress field
ρ : density of the rock
Z_i : gravitational acceleration components
a_i : acceleration components

The boundary conditions are: vanishing tractions $T_i = \sigma_{ij} n_j$ (n_j is the component of surface normal) on the free surface. The tractions (or displacements) on the other five surfaces of the crustal block can be specified only to the same degree of accuracy as our knowledge of the real physical boundary conditions.

The second important property in the problem is the presence of different structural elements such as layering, internal discontinuities and their geometrical orientations.

The third important consideration is the material properties of the various elements com-

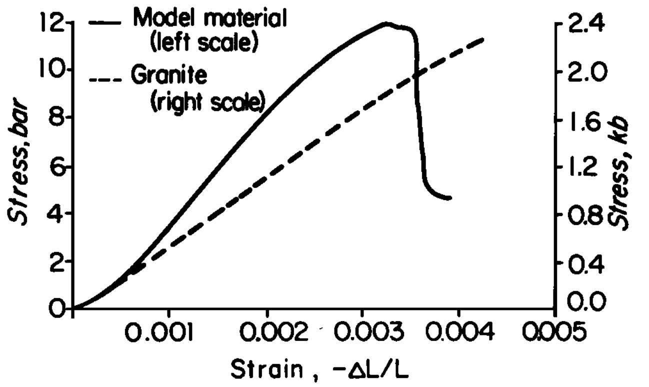

Fig. 1. Uniaxial stress-axial strain test curve of the chromite-gypsum mortar used in the construction of the crustal block. A uniaxial stress-axial strain test curve of granite (after Brace et. al., 1966) is also shown for comparison.

prising the crustal block. For example, the model material in the present work, matching the prototype, is a brittle solid.

When the above three conditions -- stress equations and boundary conditions, distribution of structural elements, and material properties -- are specified, the problem is mechanically determinate.

Next we consider the scaling of the problem in a centrifuge. We denote the quantities associated with the prototype by the subscript "p" and those associated with the model by the subscript "m". The scaling ratios are:

$$\begin{aligned} (x_i)_p &= n_\ell (x_i)_m \\ \rho_p &= n_\rho \rho_m \\ (Z_i)_p &= n_g (Z_i)_m \\ (\sigma_{ij})_p &= n_\sigma (\sigma_{ij})_m \end{aligned} \qquad (2)$$

where n_ℓ, n_ρ, n_g, and n_σ are the length, the density, the gravity and acceleration, and the stress modeling ratios of the prototype to the model respectively. Material property modeling ratios such as those of strength and deformation moduli are also given by n_σ since they all have the same dimension as that of the stress. Gravity is important in the tectonic problems since it produces significant deformation as compared to the boundary stresses. The material properties also depend on the local stresses which are gravitationally affected. When n_g <1, equation (2) corresponds to performing the model experiment in a centrifuge.

Substitute the scaling ratios into equation (1),

$$\frac{n_\sigma}{n_\ell n_\rho n_g} \sum_j \left(\frac{\partial \sigma_{ij}}{\partial x_j}\right)_m + \rho_m (Z_i)_m = \rho_m (a_i)_m, \quad i=1,3 \qquad (3)$$

Similarity is observed if we choose

$$n_\sigma = n_\ell n_\rho n_g \qquad (4)$$

The crucial importance of doing model testing in a centrifuge can be appreciated by examining equation (4). If we model without a centrifuge, n_g=1. n_ρ = 1 because the choice of rock-like modeling material is limited. Therefore $n_\sigma = n_\ell$. A typical reduction of length scale in geological problems from the prototype to the model of 10^4 implies a reduction of strength and deformation moduli of the same magnitude. This puts an extreme demand on the behavior of the modeling material. Take the prototype material of granite, for example, whose strength at zero confining pressure is on the order of 2.3 kb. A strength reduction of 10^4 means that we would need a modeling material whose strength is on the order of 0.2 bars and still exhibits the same brittle behavior as granite. Such a material is difficult to identify. However, if we model with artificial gravity in a centrifuge by choosing n_g = 1/50 for example, $n_\rho \cong 1$ as before, a length reduction of 10^4 now implies a stress and strength reduction of 200, i.e., n_σ = 200. Taking the example of granite again, we find the desired strength of the modeling material to be on the order of 12 bars. This can indeed be achieved by either chemical grouting (e.g. Terzaghi and Peck, 1967) or by mixing sand, gypsum, and water (e.g. Sabnis and White, 1967) to make the desired weak yet brittle modeling material. The plastic behavior of the fault gouge material can also be modeled by modeling clay (McClay, 1976).

If, in addition, the structural elements in the model are geometrically similar to the prototype, we can expect the model and the prototype to have physically similar strain fields.

Fracture Events in a Model Thrust Fault Loaded by Simulated Tectonic Stresses and Subjected to 50 g in a Centrifuge

Experimental Arrangement

The modeling material used is chromite sand (No. 325 sieve, grain size < 44 μm) cemented with

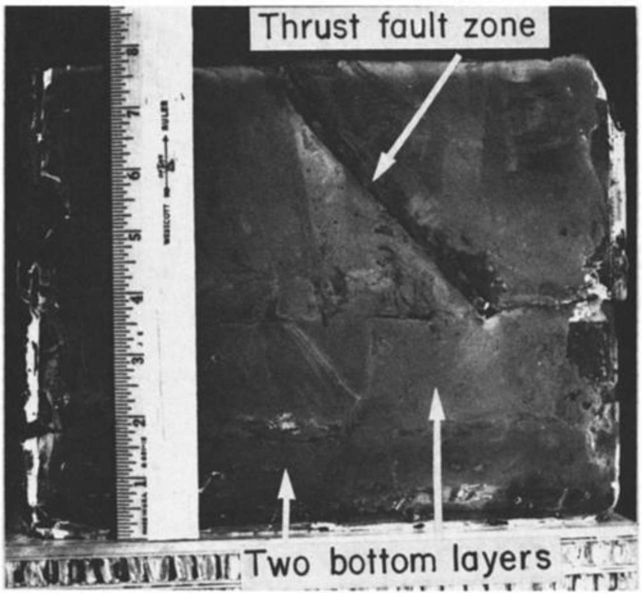

Fig. 2. Side view of the model crustal block showing the structural elements.

gypsum. The strength of the modeling material with a mixing ratio of 1:6.6:33.3 gypsum:water: chromite by weight and dried for 1 week at 75°C is ∿12 bars. Its density is 2.9 gm/c.c. A uniaxial stress-axial strain test curve of this material is shown in Figure 1. A uniaxial stress-axial strain curve for granite given by Brace et. al. (1966) is also shown for comparison. We have not determined the axial stress-volume strain relation of this material. However, gypsum-sand mortar has been demonstrated to exhibit positive dilatant behavior similar to those of crystalline rocks (Sabnis and White, 1967). Figure 2 shows the structural elements of the model. The model has two layers about 4.5 cm thick at the bottom, and two blocks 11 cm thick are separated by a built-in thrust fault zone with a dip angle of approximately 45°. The fault zone is also made of a gypsum-chromite sand mixture only that the mixing ratio is 1:30:150 gypsum:water:chromite by weight. Figure 3 shows a top surface view of the experimental arrangement. The model sits upon an L-shaped carriage which rests on two low friction linear bearings (friction coefficient = 0.001). One side of the model is loaded by the carriage wall and the opposite side of the model is loaded against the enclosure box. The lateral confinement of the model is provided by heavy grease sealed in plastic bags. The lateral confinement pressure is therefore approximately $\rho_g Gz$ where ρ_g is the density of the grease, G is the centrifugal acceleration, and z is the depth from the top. Plasticine modeling clay is used to seal the gaps between the model carriage and the enclosure box. These gaps (∿0.6 cm wide) allow boundary deformations of the model to take place during the simulated tectonic stress loading. The load on the carriage wall is produced by a hydraulic cylinder acting against a loading platen. The model carriage, the enclosure box, and the loading platen are made of 1.27 cm thick honeycomb aluminum plates reinforced by 0.397 cm

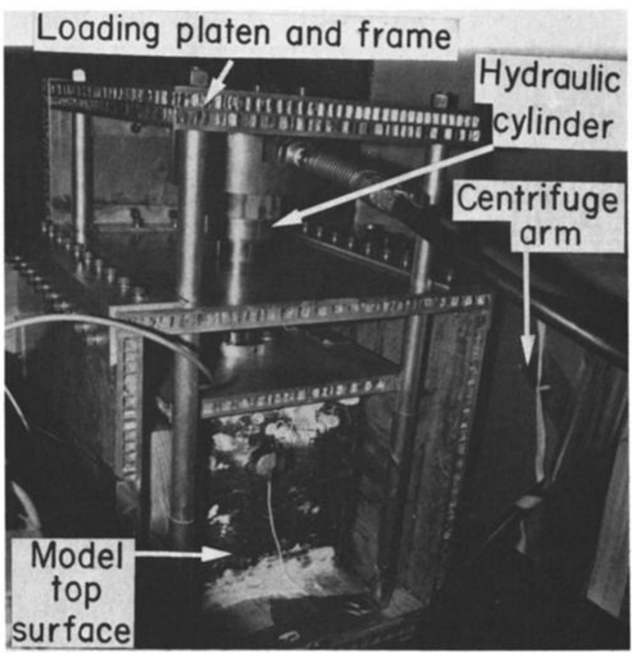

Fig. 3. Experimental arrangement of the model and the loading device.

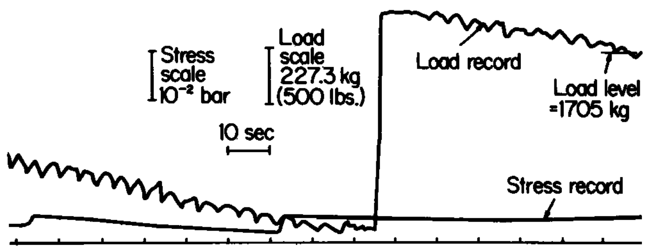

Fig. 4. Segment of the load and stress change record showing stress drop of two fracture events. The fluctuation in the total load is due to a leak in the handpump actuating the loading hydraulic cylinder. The large offset in the load record is produced by recentering of the visicorder and does not represent a change in load.

thick aluminum plates bonded by epoxy to the outside surfaces. The entire experimental package is then bolted to one base plate of the centrifuge arm. A balancing weight of the same mass and the same position of the center of gravity as those of the experimental package is fastened to the base of the opposite arm. The centrifuge is Gyrex model 2178, 1.53 m in radius and has a capacity of 11364 g-kg.

The instrumentation of the experiment consists of the following: One BLH miniature load cell is situated between the hydraulic cylinder and the carriage wall to measure the total loading force. One Kulite miniature pressure transducer (0.95 cm x 0.4 cm x 0.08 cm in dimensions) is buried in the fault zone 4.5 cm down slope from the model top surface. The orientation of the pressure gage is perpendicular to the fault surface and intersecting with the fault plane in a line parallel to the model top surface. A ceramic piezoelectric transducer (1.9 cm diameter, compressional mode, 750 kHz resonance frequency) is glued by epoxy to the model top surface. The miniature pressure transducer is installed to monitor local stress change in the fault zone and the piezoelectric transducer is employed to monitor the acoustic signals of the fracture events. The outputs of the load cell and the pressure transducer are measured by Wheatstone bridge circuits and recorded on a Honeywell model 906A Visicorder after voltage magnification. The signal from the piezoelectric transducer is amplified by a low noise pre-amplifier mounted on the centrifuge. The electric signals are transmitted through the slip rings and recorded on a magnetic tape recorder. The hydraulic cylinder is actuated through a hydraulic swivel head on the Gyrex centrifuge.

Results

Fracture events were recorded when the model was at 50 g and subjected to an increasing load beginning at 1478 kg. Ten events were recorded before loading stopped at 2360 kg. Figure 4 shows the load and a typical stress drop record obtained in the fault zone by the Kulite miniature pressure transducer. Figure 5 shows a typical model seismogram recorded by the piezoelectric transducer on the model top surface. The high frequency components of the stress drop were filtered out because of the low cut-off

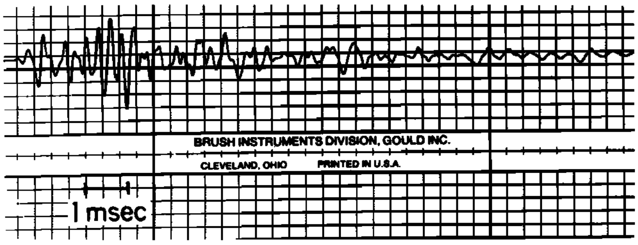

Fig. 5. A model seismogram recorded on the model top surface. Amplitude not calibrated.

frequency of the DC amplifier (3 dB point at 0.45 Hz) used for the bridge circuit. However, the instrument response of the acoustic radiation measurement device (>10 kHz), which is approximately three times higher than the highest frequency of the acoustically radiated signal, is adequate to cover the frequency spectrum of the model seismogram. These fracture events are considered to be localized since no visible traces of fault offset were discovered after the experiment. Taking granite as the prototype material, the stress scaling ratio is $n_\sigma = 2.3$ kb/12 bars $\cong$ 200 and the density scaling ratio is $n_\rho = (2.6 \text{ gm/c.c.})/(2.9 \text{ gm/c.c.}) = 0.9$. Since $n_g = 1/50$ in the experiment, the length scaling ratio is $n_\ell = n_\sigma / n_\rho n_g = 11154$. The time scaling ratio is $n_t = \sqrt{n_\ell / n_g} = 707$. The model therefore scales up to a prototype approximately 2.2 km x 2.8 km x 3.0 km in dimensions. The highest frequency in the model seismogram scales down to approximately 12 Hz in the prototype. The amplitude of the seismogram has not been calibrated.

Discussions

We have demonstrated the feasibility of modeling in a centrifuge dynamically similarly fracture events in a crustal block. The values of such modeling experiments in geophysical investigations are:

(1) The tests are conducted under controlled conditions as compared with the naturally occuring events. The boundary forces and displacements, the modeling material behavior, and the structural elements of the model are under the control of the experimenter. With further development of measuring techniques such as the determination of surface deformation during the experiment, and the determination of internal displacements by X-ray methods, many empirical, theoretical, and numerical studies in geophysics involving fracture with non-linear material behavior and surrounded by complex structures could be tested by the centrifuge modeling technique (e.g. earthquake precursory phenomena and focal source theories).

(2) Model tests could eventually be used to help hazard evaluation of real earthquake faults. Such an evaluation, however, must be preceded by a better understanding of the state of stress in the crust, rock behaviors (such as the failure surface in three dimensional stress space, and the influence of grain size on fracture), the structural elements of the fault, and the permeability of rocks and the ground water flow considerations. Suitable modeling materials and a large capacity centrifuge are also prerequisites to such an endeavor.

Centrifuge modeling techniques have been employed in engineering and geotechnical investigations (Scott, 1975). Ramberg and his coworkers (e.g. Ramberg, 1967) have carried out a series of centrifuge tests modeling geological viscous and plastic deformation processes under the driving force of gravity. The present work extends the centrifuge technique to the modeling of brittle fracture phenomena associated with crustal earthquakes generated by tectonic stresses.

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